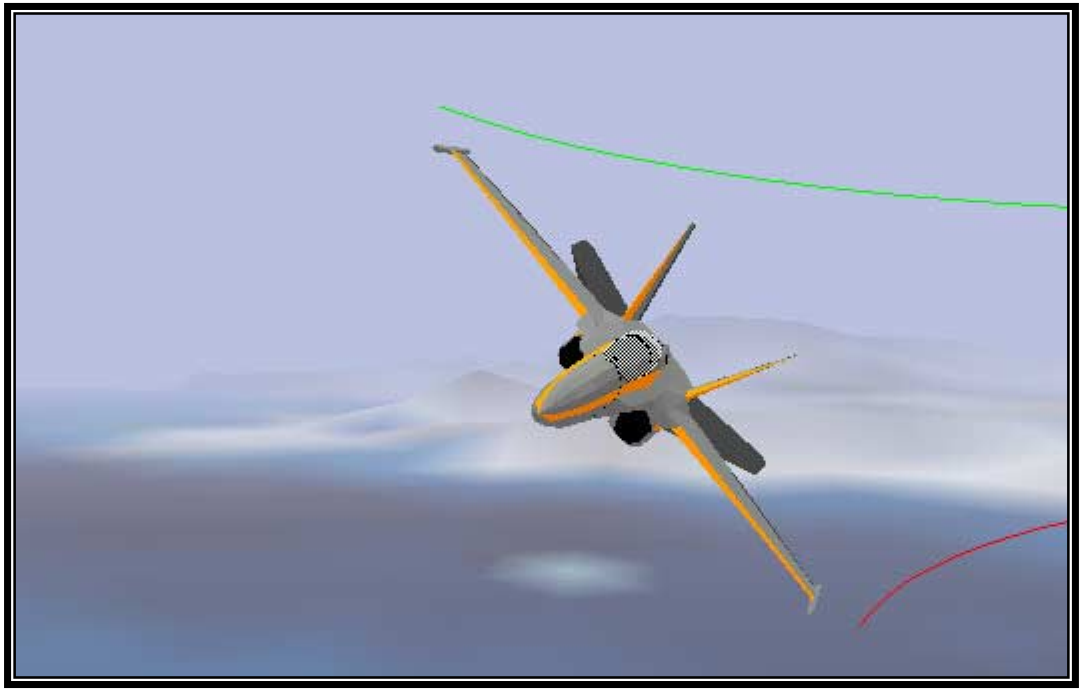
Aerobatics Maneuvering & UAV* Coordination



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Quarterly Review - January, 2001

*Uninhabited Air Vehicles

Outline

- Introduction
- Control law for nonlinear UAV model
  - Trajectory tracking
  - Barrel roll test
  - Extension for fixed throttle operations
- A rule-based controller simulation
  - Rule-based scheduler presentation
  - Simulation architecture
  - Simulation results
- Concluding remarks

Introduction

- **Emerging roles for UAVs**
  - **Expansion of their intelligence gathering role**
  - **Engagement in combat**
  - **Operation in confined airspaces**
- **New requirements**
  - **High maneuverability**
  - **Concerted action (fly different paths for mutual support)**
- **Our interest**
  - **Aerobatics maneuvering**
  - **Coordination of UAV teams**

UAV Nonlinear Model

- **Assumptions**
  - Three time differentiable trajectory specified in earth coordinates, $x_e(t)$
  - No sideslip
- **Notations**

  d - desired value

  e - earth frame

  b - body frame

  w - wind frame

  $\mathbf{H}_1^2$ - transformation from frame 1 to frame 2

  I - inertia matrix

- **Dynamics equations**
  - Split into fast mode

$$\begin{cases} \dot{\boldsymbol{\omega}}_b = \mathbf{I}^{-1}\left[\mathbf{M}_b - \boldsymbol{\omega}_b \times \mathbf{I}\boldsymbol{\omega}_b\right] \\ \boldsymbol{\omega}_w = \mathbf{H}_b^w \boldsymbol{\omega}_b \\ \mathbf{a}_w = \mathbf{a}_w(\alpha, \beta, T) \end{cases}$$

  - and slow mode

$$\begin{cases} \dddot{\mathbf{x}}_e = \mathbf{g} + \mathbf{H}_w^e \mathbf{a}_w \\ \dot{\mathbf{H}}_w^e = \mathbf{H}_w^e \hat{\boldsymbol{\omega}}_w \end{cases}$$

See J. Hauser et al.,

"Aggressive Flight Maneuvers"

Trajectory Tracking
Outer Loop

- **State feedback linearization**
  - **Desired trajectory third derivative:**

$$\dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} = \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \omega_{w2} a_{w3} \\ \omega_{w3} a_{w1} \\ -\omega_{w2} a_{w1} \end{bmatrix} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}} \begin{bmatrix} \dot{a}_{w1} \\ -a_{w3}\omega_{w1} \\ \dot{a}_{w3} \end{bmatrix}$$

  - **Linearizing control law:**

$$\begin{bmatrix} \dot{a}_{w1}^{d} \\ -a_{w3}\omega_{w1}^{d} \\ \dot{a}_{w3}^{d} \end{bmatrix} = \begin{bmatrix} -\omega_{w2} a_{w3} \\ \omega_{w3} a_{w1} / a_{w3} \\ \omega_{w2} a_{w1} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1/a_{w3} & 0 \\ 0 & 0 & 1 \end{bmatrix} \mathbf{H}_{\mathbf{w}}^{\mathbf{e}\,\mathrm{T}} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

$$\mathbf{u} = \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} + k_2(\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \ddot{\mathbf{x}}_{\mathbf{e}}) + k_1(\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \dot{\mathbf{x}}_{\mathbf{e}}) + k_0(\mathbf{x}_{\mathbf{e}}^{\mathbf{d}} - \mathbf{x}_{\mathbf{e}})$$

Can be solved for ω_{w1}^{d} if $a_{w3} \neq 0$

Trajectory tracking
Inner Loop

- **Nonlinear dynamic inversion**

$$\dot{\alpha}^d = -2m\dot{a}^d_{w3} \big/ (\rho SV^2 C_{L\alpha})$$

$$\dot{\beta}^d = 2m\dot{a}^d_{w2} \big/ (\rho SV^2 C_{Y\beta})$$

$$\dot{a}^d_{w2} = -k_\beta a_{w2}$$

$$\boldsymbol{\omega}_\mathbf{b}^\mathbf{d} = \begin{bmatrix} 0 \\ \dot{\alpha}^d \\ 0 \end{bmatrix} + \mathbf{H}_\mathbf{w}^\mathbf{b} \begin{bmatrix} \omega^d_{w1} \\ -(a_{w3} + g_{w3})/V \\ g_{w2}/V - \dot{\beta}^d \end{bmatrix}$$

  - **Body torque computation**

$$\mathbf{M}^d = K\,\mathbf{I}(\boldsymbol{\omega}_\mathbf{b}^\mathbf{d} - \boldsymbol{\omega}_\mathbf{b}) + \boldsymbol{\omega}_\mathbf{b} \times \mathbf{I}\boldsymbol{\omega}_\mathbf{b}$$

  - **Actuator deflection computation**

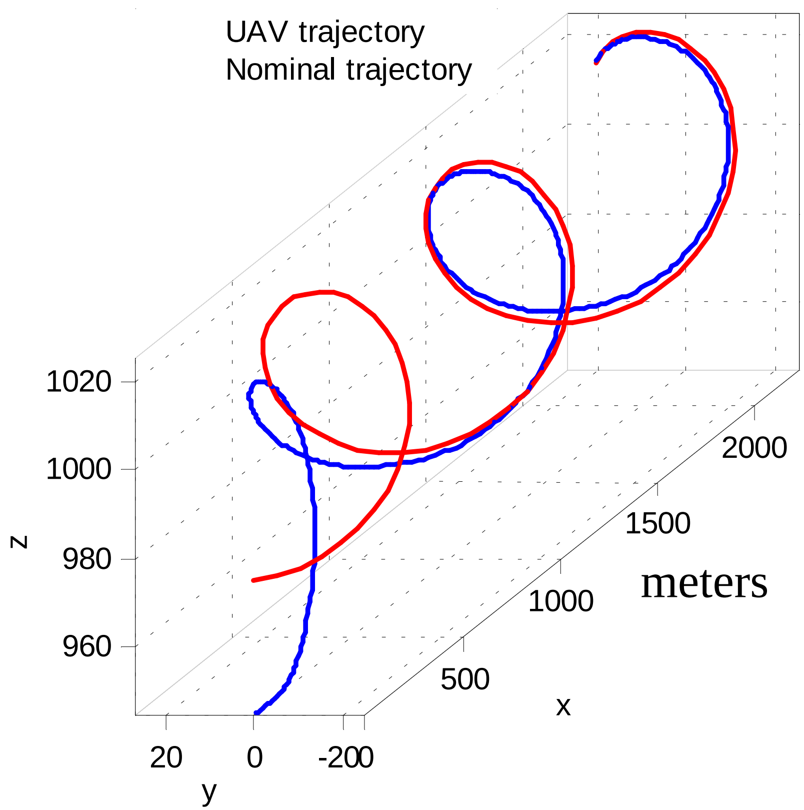
$$\begin{bmatrix} \text{aileron} \\ \text{rudder} \end{bmatrix} = \begin{bmatrix} C_{l\delta a} & C_{l\delta r} \\ C_{n\delta a} & C_{n\delta r} \end{bmatrix}^{-1} \begin{bmatrix} L\big/\tfrac{1}{2}\rho SbV^2 - C_{l\beta}\beta - \tfrac{2b}{V}C_{lp}\omega_{b1} - \tfrac{2b}{V}C_{lr}\omega_{b3} \\ N\big/\tfrac{1}{2}\rho SbV^2 - C_{n\beta}\beta - \tfrac{2b}{V}C_{np}\omega_{b1} - \tfrac{2b}{V}C_{nr}\omega_{b3} \end{bmatrix}$$

$$\text{elevator} = \frac{1}{C_{m\delta e}}\left[M\big/\tfrac{1}{2}\rho S\bar{c}V^2 - C_{m0} - C_{m\alpha}\alpha - \tfrac{2\bar{c}}{V}C_{mq}\omega_{b2}\right]$$

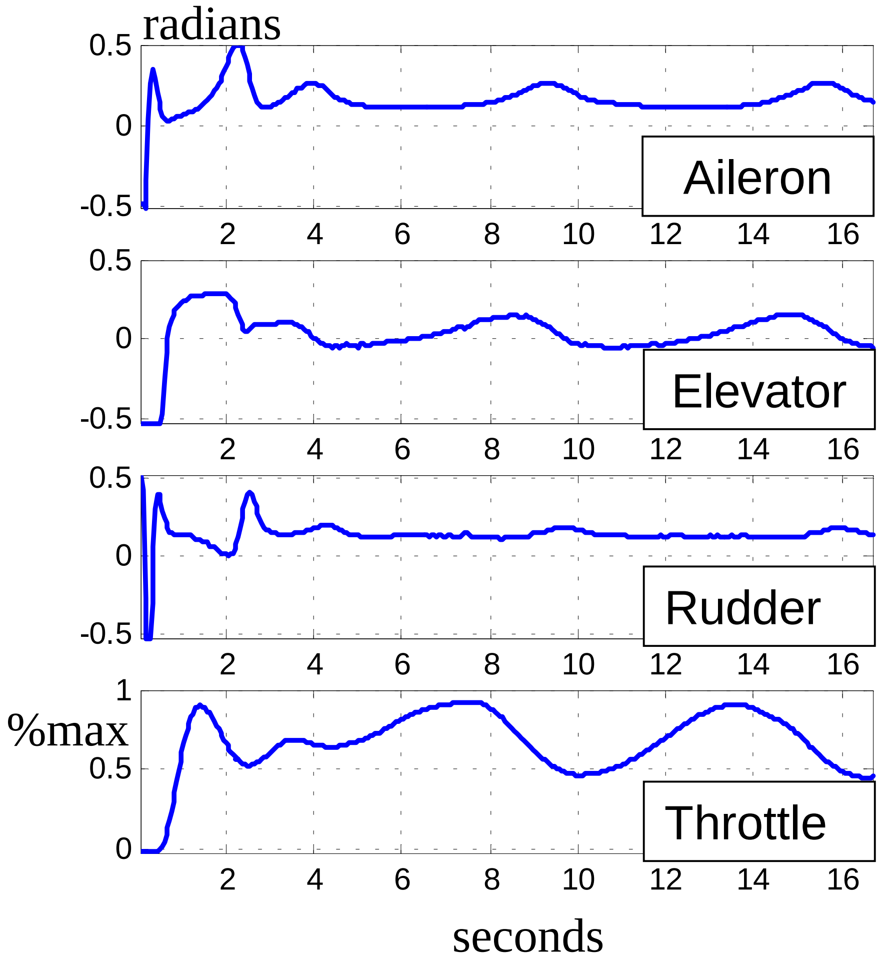
$$\dot{T} = \dot{T}(\dot{a}^d_{w1}, \alpha, \dot{\alpha}^d)$$

Barrel roll test

- **3D view of the UAV trajectory**



- **Control inputs used**



Control law discussion

- **Limitations**
  - No post-stall or parabolic trajectory supported
  - Cannot roll the aircraft independently from the trajectory
  - Large throttle use
  - Number of trajectory derivatives required
- **Extensions**
  - Sideslip instead of roll rate as command variable

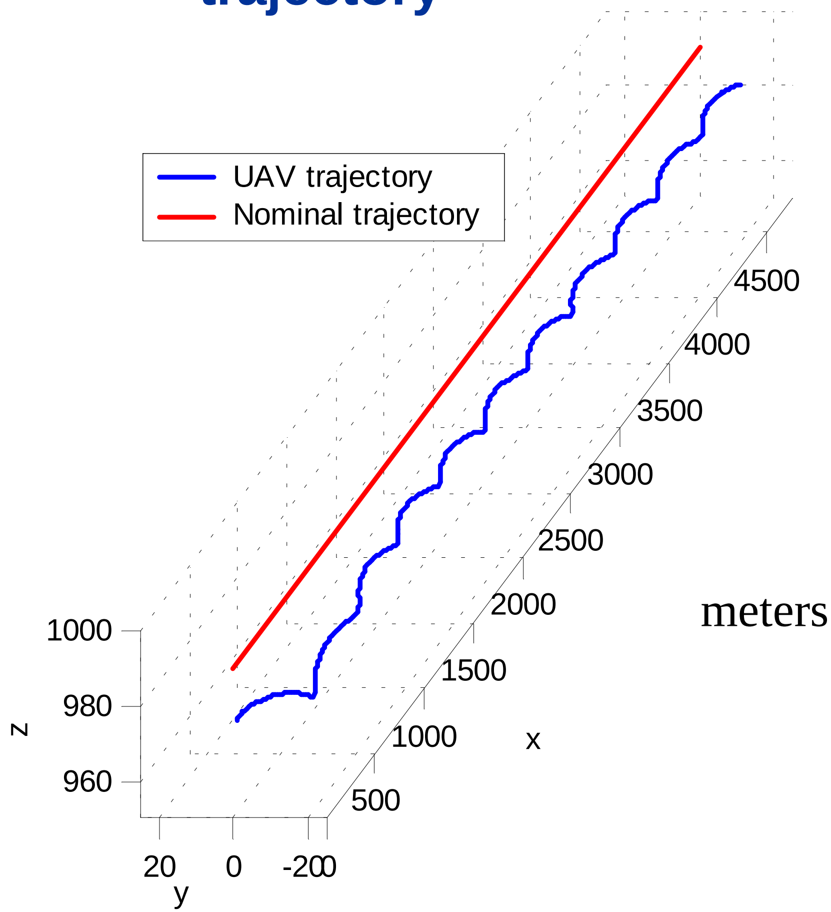
$$\begin{bmatrix} \dot{a}_{w1}^{d} \\ \dot{a}_{w2}^{d} \\ \dot{a}_{w3}^{d} \end{bmatrix} = \begin{bmatrix} \omega_{w3} a_{w2} - \omega_{w2} a_{w3} \\ \omega_{w1} a_{w3} - \omega_{w3} a_{w1} \\ \omega_{w2} a_{w1} - \omega_{w1} a_{w2} \end{bmatrix} + \mathbf{H}_{\mathbf{w}}^{\mathbf{e}\,\mathrm{T}} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

$$\omega_{b1}^{d} = \text{constant}$$

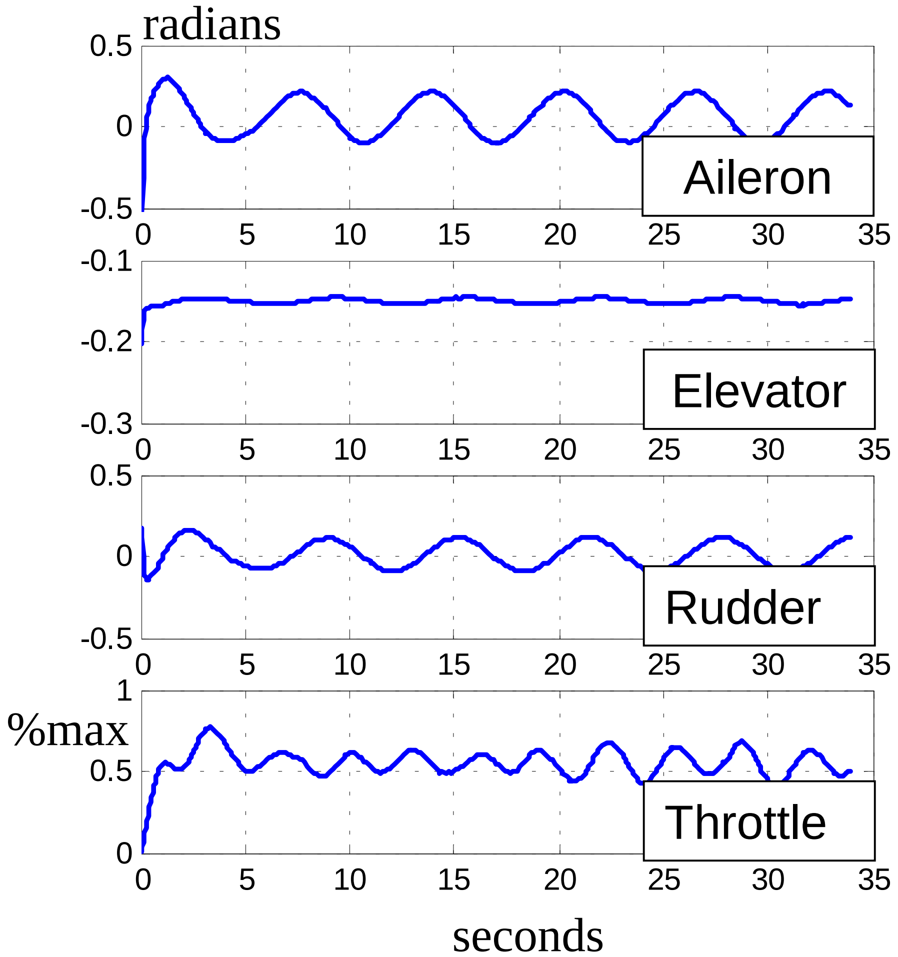
  - Fixed throttle trajectory tracking

Velocity roll test

- **3D view of the UAV trajectory**



- **Control inputs used**



Fixed throttle trajectory tracking

- **Trajectory parameterization reviewed**

$$\mathbf{x}_{\mathbf{e}}^{\mathbf{D}}(t) = \mathbf{x}_{\mathbf{e}}^{\mathbf{d}}\{s(t)\} \text{such that } s(t) = \text{equivalent path length}$$

- **New command**

$$\mathbf{u} = \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} + k_2(\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \ddot{\mathbf{x}}_{\mathbf{e}}) + k_1(\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \dot{\mathbf{x}}_{\mathbf{e}}) + k_0(\mathbf{x}_{\mathbf{e}}^{\mathbf{d}} - \mathbf{x}_{\mathbf{e}})$$

replaced by

$$\mathbf{u} = \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)\dot{s}^3 + 3\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)\ddot{s}\dot{s} + \dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)\dddot{s} + k_2(\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \ddot{\mathbf{x}}_{\mathbf{e}}) + k_1(\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}} - \dot{\mathbf{x}}_{\mathbf{e}}) + k_0(\mathbf{x}_{\mathbf{e}}^{\mathbf{d}} - \mathbf{x}_{\mathbf{e}})$$

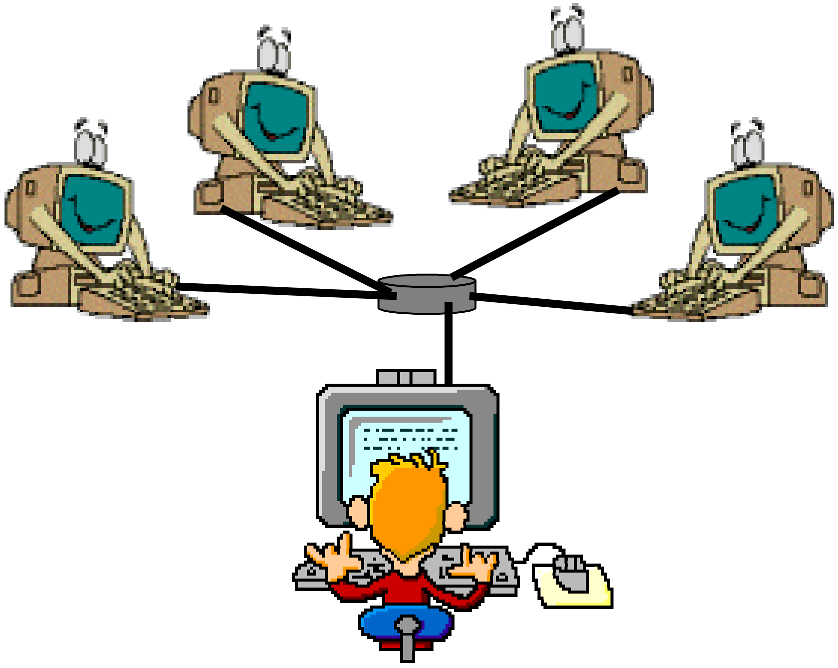
- **New linearizing control law**

$$\begin{bmatrix} \vdots & 0 & 0 \\ \mathbf{H}_{\mathbf{e}}^{\mathbf{w}}\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s) & a_{w3} & 0 \\ \vdots & 0 & -1 \end{bmatrix} \begin{bmatrix} \dddot{s}^d \\ w_1^d \\ \dot{a}_{w3}^d \end{bmatrix} = \begin{bmatrix} \omega_{w2}a_{w3} + \dot{a}_{w1} \\ \omega_{w3}a_{w1} \\ -\omega_{w2}a_{w1} \end{bmatrix} - \mathbf{H}_{\mathbf{e}}^{\mathbf{w}}\left[3\ddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)\ddot{s}\dot{s} + \dddot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)\dot{s}^3 + k_2\ddot{\mathbf{e}} + k_1\dot{\mathbf{e}} + k_0\mathbf{e}\right]$$

where $\mathbf{e}(t) = \mathbf{x}_{\mathbf{e}}^{\mathbf{D}}(t) - \mathbf{x}_{\mathbf{e}}(t)$

First matrix invertion possible if $\dot{\mathbf{x}}_{\mathbf{e}}^{\mathbf{d}}(s)$ is not orthogonal to $\dot{\mathbf{x}}_{\mathbf{e}}(t)$

Multi-Aircraft Simulation



- **Preliminary Objective**
  - Coordinate aerobatics maneuver execution by a team of UAV

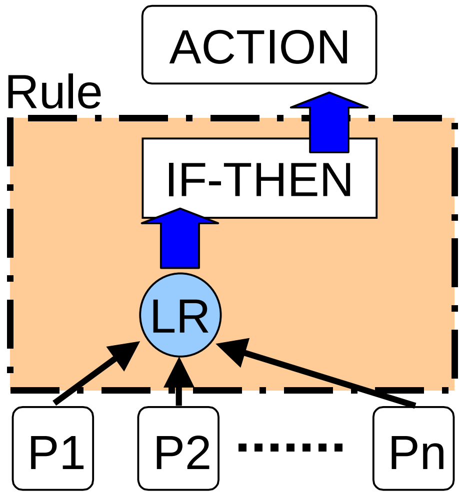
- **Environment**
  - Four computers (one per UAV)
  - Communications through the local area network

- **Method**
  - Trajectory position broadcasting
  - Logic to choose an aircraft as reference (rule-based controller)
  - Timing taking advantage of the fixed throttle control law

Rule-based Scheduler Presentation

- **Rule base paradigm**

  ⇒ Production rules applied to a database storing the parameters by matching premises

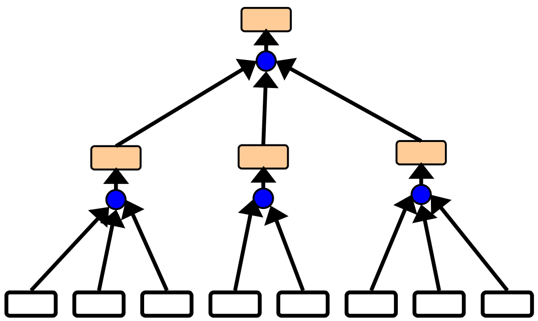


LR: Logical Relation (AND,OR)

P1,…,Pn: Premises 1 to n

Action and Premises are either parameters or procedures returning a value.

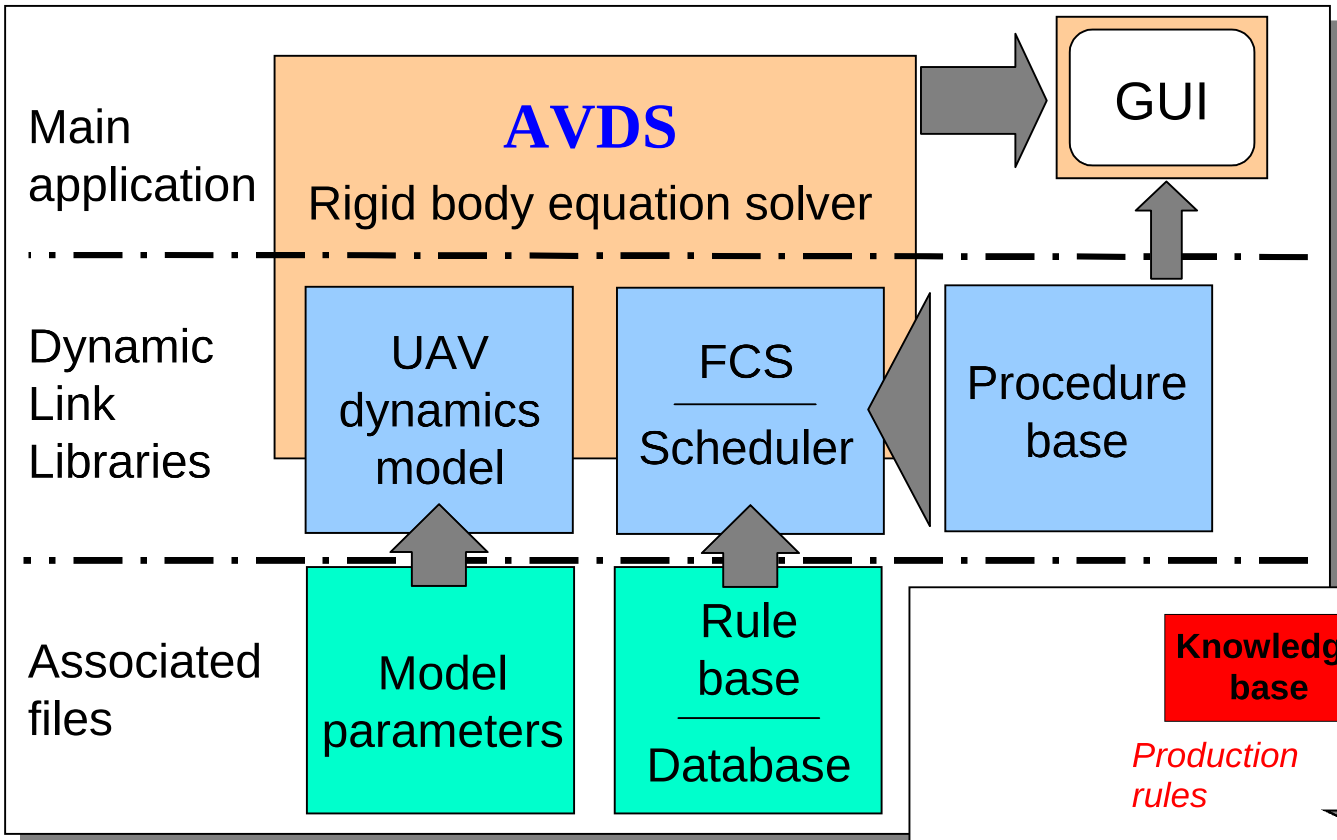
- **Rule-based scheduler**
  - 1 to 1 relation between actions and rules
  - Hierarchical structure of rules



  - Uses THEN or SYNC as logical relations between tasks
  - Leaves of the tree are procedures representing subtasks while the root is the main task.
  - Parameters take values:

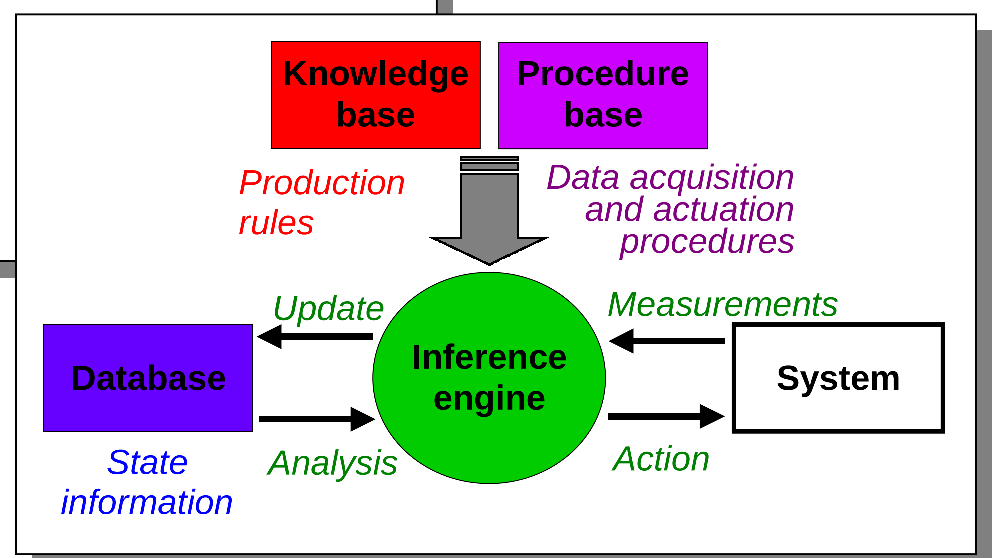
    “Done”, “Not Done”

Simulation Architecture



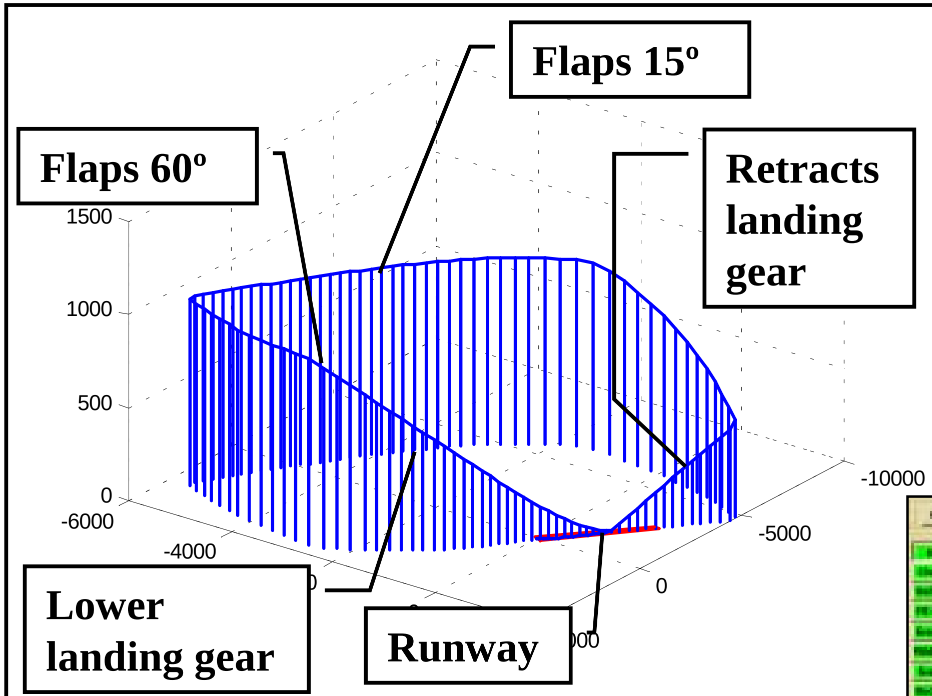
- **Code architecture**

  Highly modular for maintainability



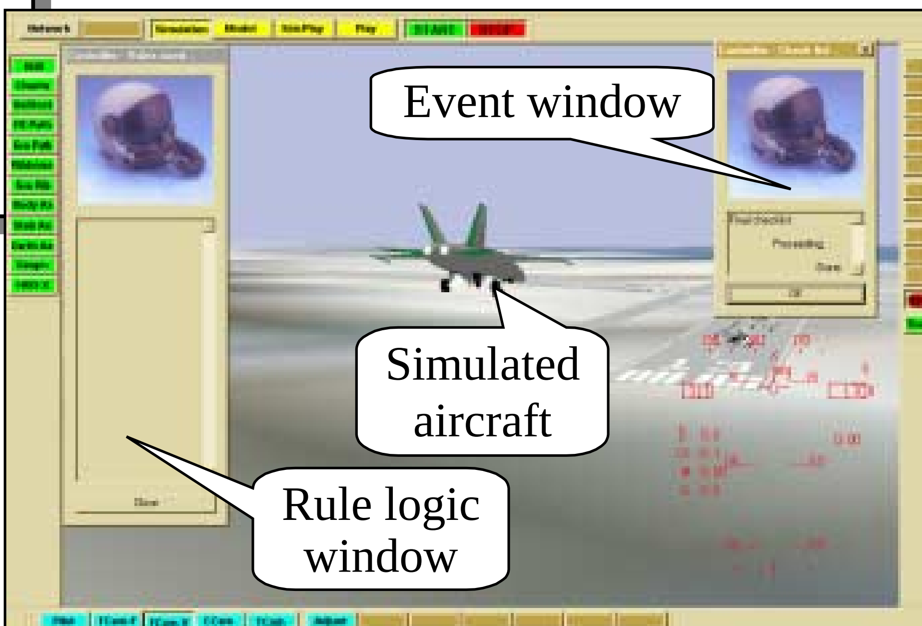
- **Rule-based scheduler structure**

Simulation Results



- **Airport traffic pattern flight simulation**
  - **Aircraft configuration**
  - **Waypoints sequence managed by the rule-base scheduler**

- **Simulation visual interface**
  - **Tools are provided for the user to follow the rule-based logic**
  - **Tools for user interaction with the simulation are under development**



Concluding Remarks

- **Aerobatics Maneuvering:**
  - A control law to track trajectories specified in earth coordinates.
  - Extensions for fixed throttle operations
- **Aircraft coordination**
  - Aircraft timing along trajectories
  - Rule-based controller for logical reasoning
  - Subsystems fusion to be done
- **Future work:**
  - Demonstration by a sample air show sequence
  - Team reconfiguration after failure of an aircraft